The Cool Copper Collider: An Advanced Concept for a Future Higgs Factory

Emilio Nanni
Snowmass
7/22/2022

Acknowledgements

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Strategy for Understanding the Higgs Physics: The Cool Copper Collider

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C^3 Demonstration Research and Development Plan

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C^3 : A "Cool" Route to the Higgs Boson and Beyond

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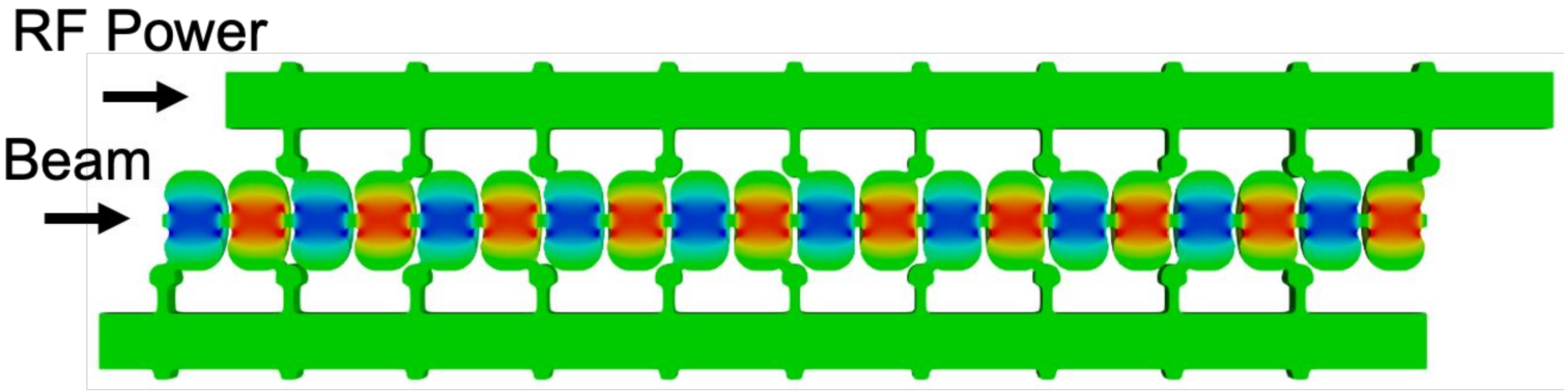
More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

A novel route to a linear e^+e^- collider…

Breakthrough in the Performance of RF Accelerators

RF power coupled to each cell – no on-axis coupling

Full system design requires modern virtual prototyping



Electric field magnitude produced when RF manifold feeds alternating cells equally

Optimization of cell for efficiency (shunt impedance)

$$R_s = G^2/P \text{ [M}\Omega\text{/m]}$$

- Control peak surface electric and magnetic fields

Key to high gradient operation

Tantawi, Sami, et al. *PRAB* 23.9 (2020): 092001.

Cryo-Copper: Enabling Efficient High-Gradient Operation

Cryogenic temperature elevates performance in gradient

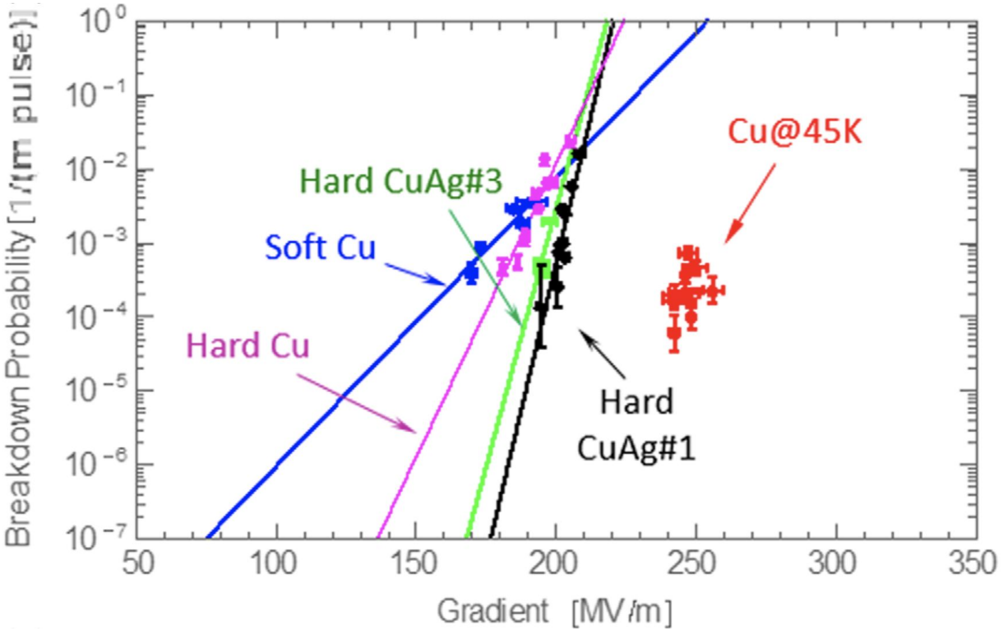
- Increased material strength is key factor
- Increase electrical conductivity reduces pulsed heating in the material

Operation at 77 K with liquid nitrogen is simple and practical

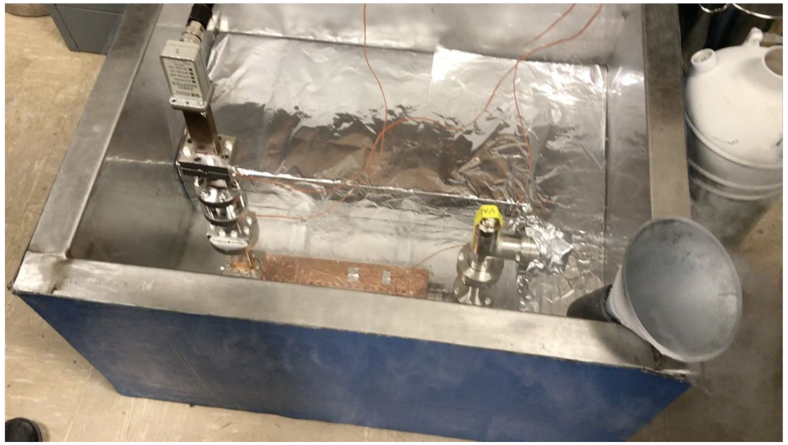
- Large-scale production, large heat capacity, simple handling
- Small impact on electrical efficiency

$$\eta_{cp} = LN\ Cryoplant$$
$$\eta_{cs} = Cryogenic\ Structure$$
$$\eta_k = RF\ Source$$

$$\frac{\eta_{cs}}{\eta_k}\eta_{cp} \approx \frac{2.5}{0.5}[0.15] \approx 0.75$$



Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.



Accelerator Complex

8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

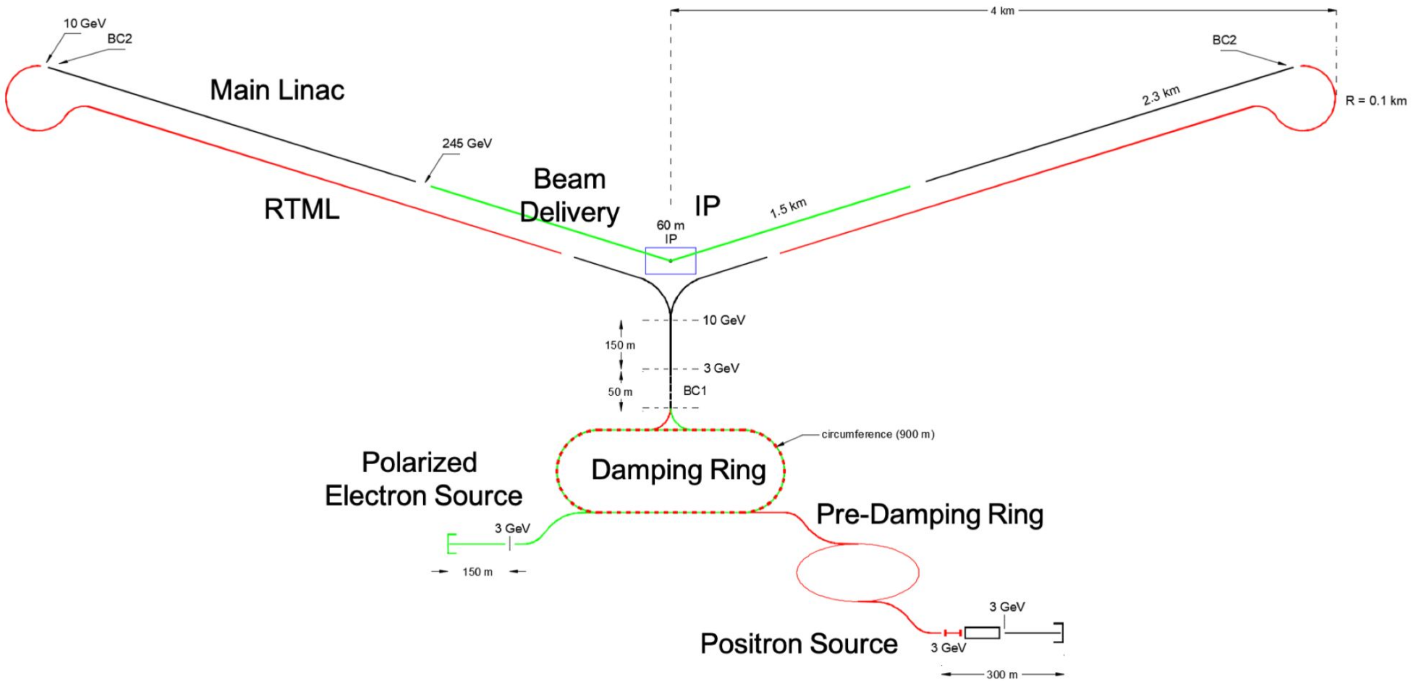
Large portions of accelerator complex are compatible between LC technologies

- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline
- Costing studies use LC estimates as inputs

C^3 Parameters

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

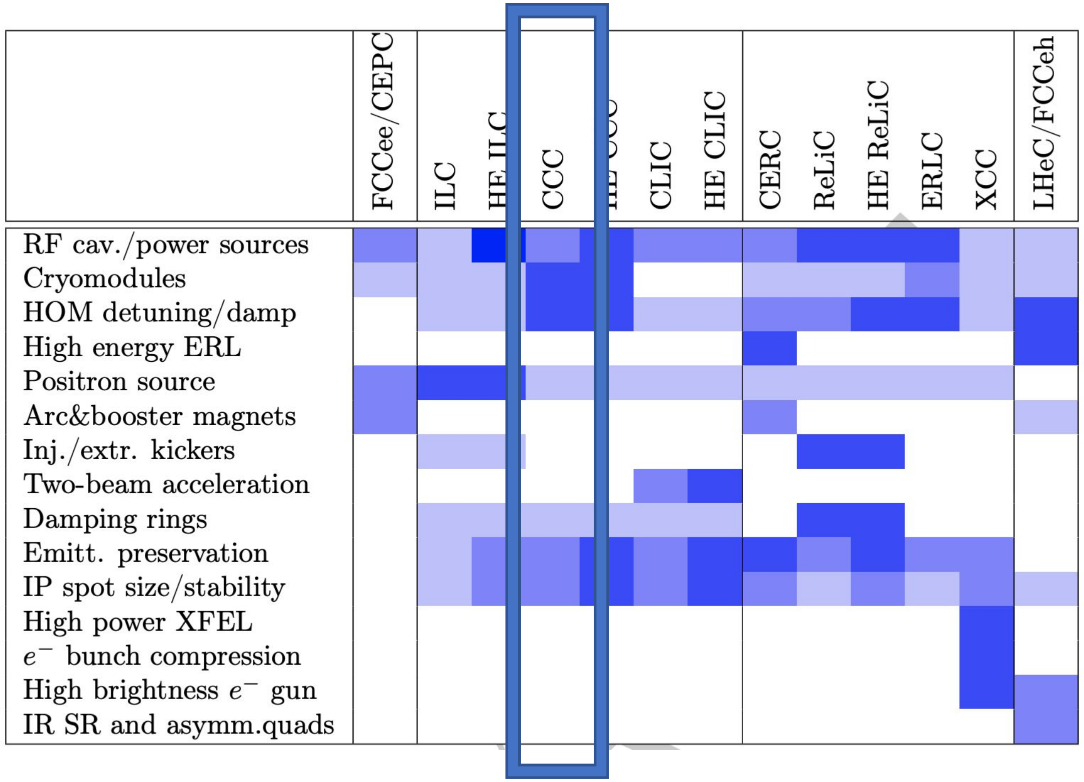
C^3 - 8 km Footprint for 250/550 GeV



Implementation Task Force Assessment for Snowmass

Great potential… need to demonstrate the approach at scale!!

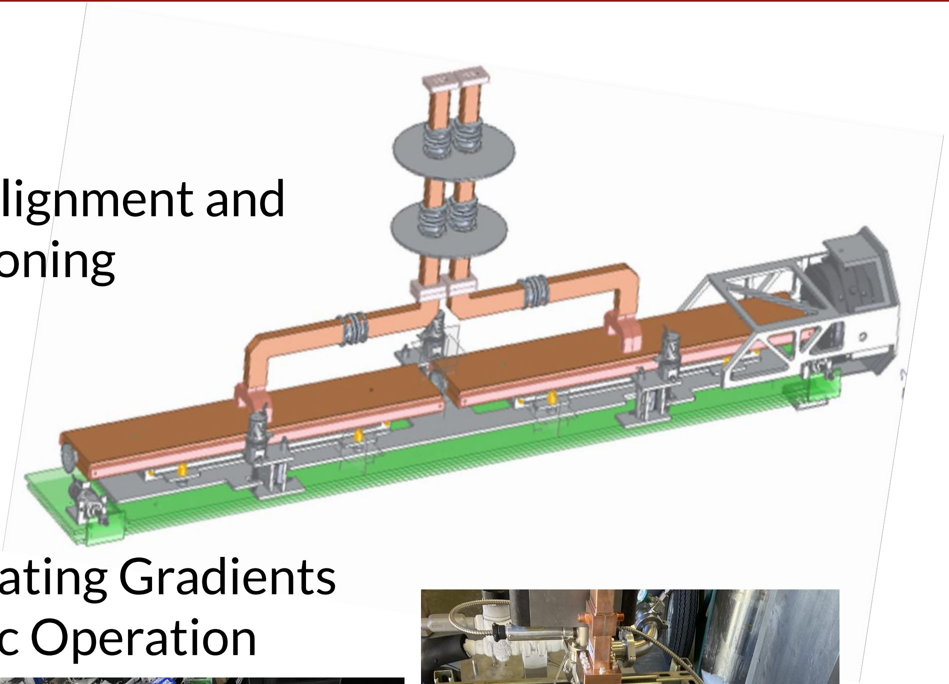
Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	280	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	14 km	I	I
CLIC (0.38 TeV)	170	13.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I
CERC (0.24 TeV)	90	100 km	II	I
ReLiC (0.24 TeV)	370	20 km	II	I
ERLC (0.24 TeV)	250	60 km	II	I
XCC (0.125 TeV)	90	1.4 km	II	I
MC (0.13 TeV)	200	3 km	I	II
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	42 km	III	II
CCC (3 TeV)	~700	26.8 km	II	II
ReLiC (3 TeV)	~780	360 km	III	I
MC (3 TeV)	~230	10-20 km	II	III
LWFA (3 TeV)	~340	1.3 km	II	I
PWFA (3 TeV)	~230	14 km	II	II
SWFA (3 TeV)	~170	18 km	II	II
MC (14 TeV)	~300	27 km	III	III
LWFA $\gamma\gamma$ (15 TeV)	~210	6.6 km	III	I
PWFA $\gamma\gamma$ (15 TeV)	~120	14 km	III	II
SWFA $\gamma\gamma$ (15 TeV)	~90	90 km	III	II
FCC-hh (100 TeV)	~560	91 km	II	III
SPPC (125 TeV)	~400	110 km	II	III



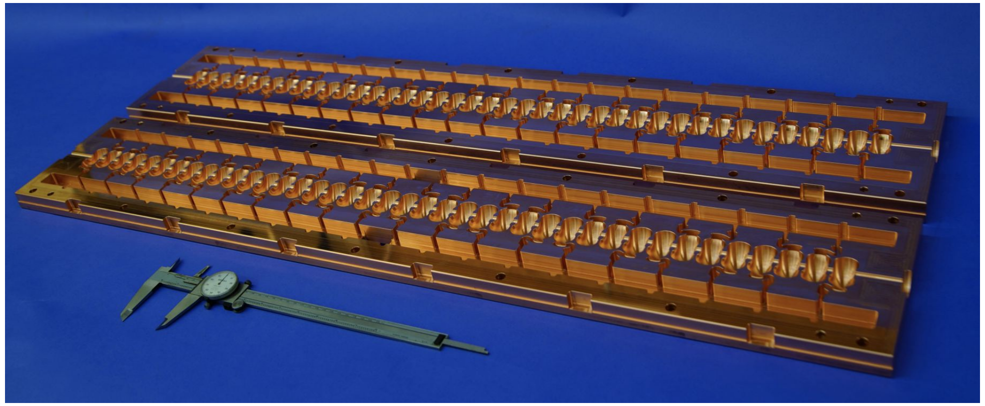
https://indico.fnal.gov/event/54953/sessions/20614/attachments/156153/205983/ITFreportDRAFT-July19.pdf

Ongoing Technological Development

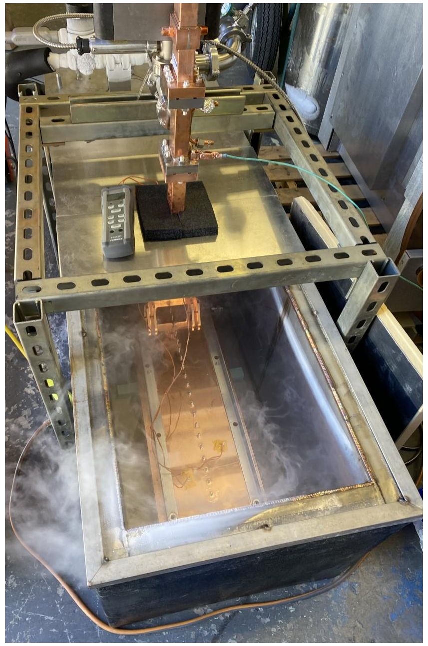
Preliminary Alignment and Positioning



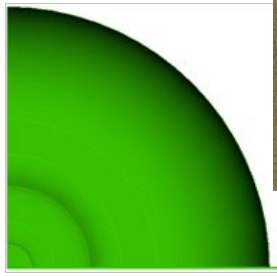
Modern Manufacturing
Prototype One Meter Structure

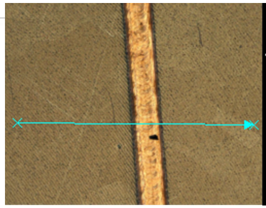


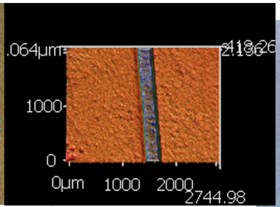
High Accelerating Gradients
Cryogenic Operation

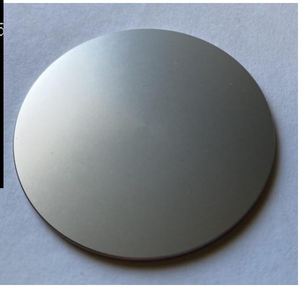


Integrated Damping
Slot Damping with NiChrome Coating









Accelerator Design and Challenges

Accelerator Design

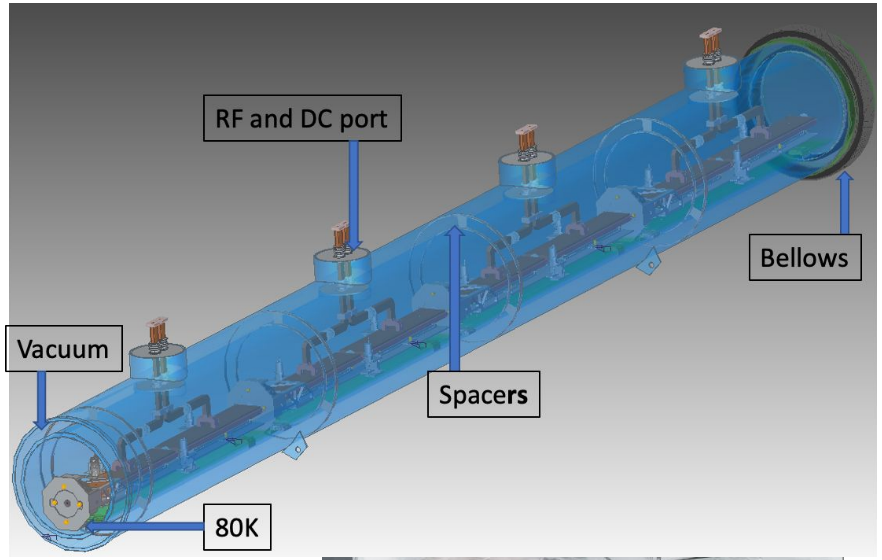
- Engineering and design of prototype cryomodule underway

Focused on challenges identified with community through snowmass (all underway)

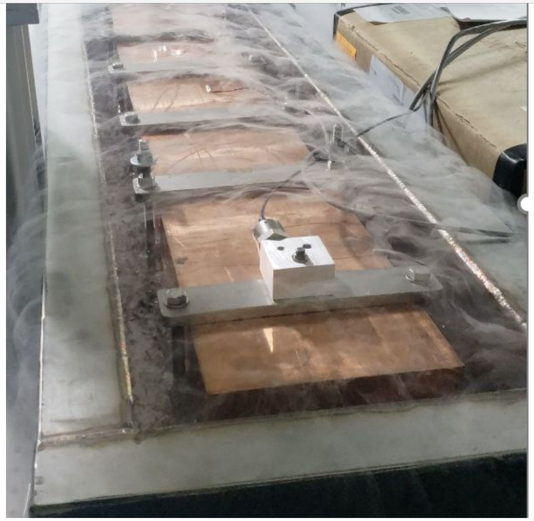
- Gradient – Scaling up to meter scale cryogenic tests
- Vibrations – Measurements with full thermal load
- Alignment – Working towards raft prototype
- Cryogenics – Two-phase flow simulations to full flow tests
- Damping – Materials, design and simulation
- Beam Loading and Stability - Thermionic beam test
- Scalability – Cryomodules and integration

Laying the foundation for a demonstration program to address technical risks beyond RDR (CDR) level

Cryomodule Concept



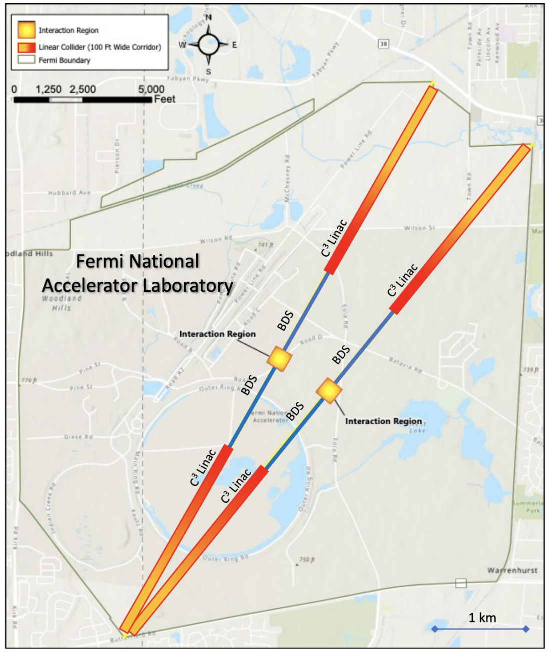
Vibration Studies



Civil Construction and Siting

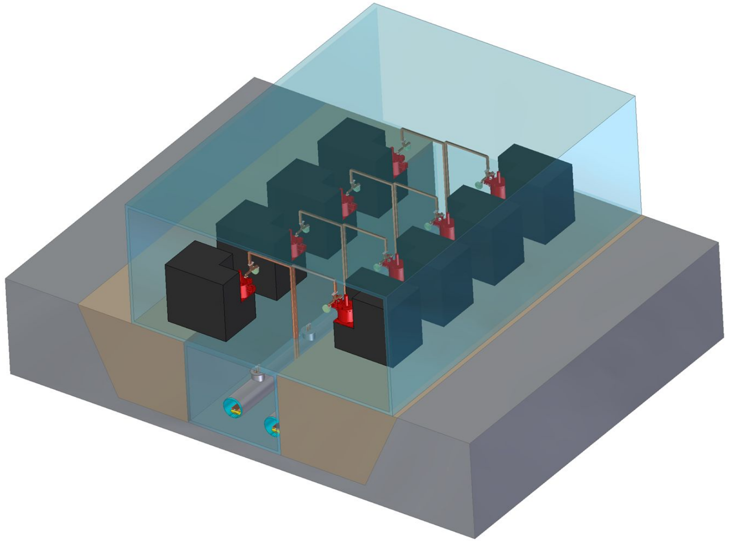
- Compact footprint <8 km for 550 GeV allows for many siting options
- Evaluating both underground and surface sites
  - Underground – less constraints on energy upgrade
  - Surface – lower cost and faster to first physics

Fermilab Site Filler



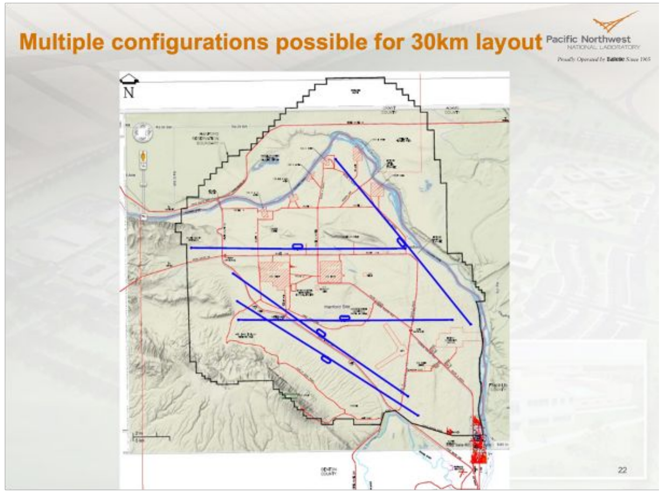
National Lab and Green Field are Possibilities

Surface-Site Mockup (Tunnel in White Paper)

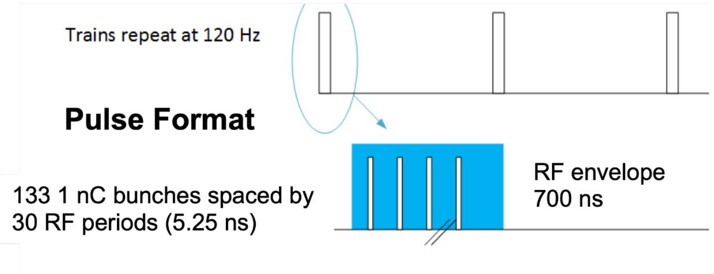


- Rapid Excavation / Parallel Installation
- No Vertical Shafts

Hanford Site

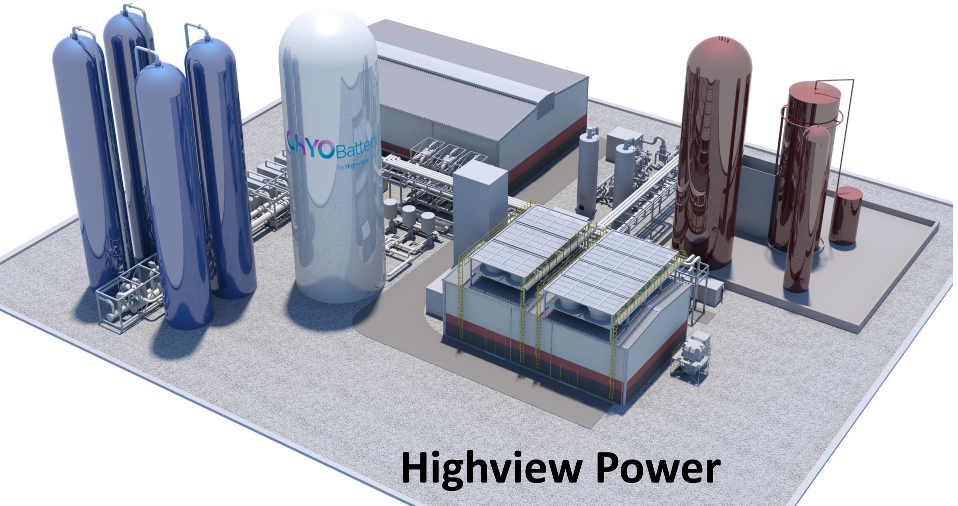


Power Consumption and Sustainability



Temperature (K)	77
Beam Loading (%)	45
Gradient (MeV/m)	70
Flat Top Pulse Length (μs)	0.7
Cryogenic Load (MW)	9
Main Linac Electrical Load (MW)	100
Site Power (MW)	~150

Compatibility with Renewables
Cryogenic Fluid Energy Storage



Highview Power

Intermittent and variable power production from renewables mediated with commercial scale energy storage and power production

250 GeV CoM - Luminosity - 1.3×10^{34}

Parameter	Units	Value
Reliquification Plant Cost	M$/MW	18
Single Beam Power (125 GeV linac)	MW	2
Total Beam Power	MW	4
Total RF Power	MW	18
Heat Load at Cryogenic Temperature	MW	9
Electrical Power for RF	MW	40
Electrical Power For Cryo-Cooler	MW	60
Accelerator Complex Power	MW	~50
Site Power	MW	~150

Upgrade Options

Luminosity

- Beam power can be increased for additional luminosity
- C^3 has a relatively low current for 250 GeV CoM (0.19 A) - Could we push to match CLIC at 1.66 A? (8.5X increase?)
- Pulse length and rep. rate are also options

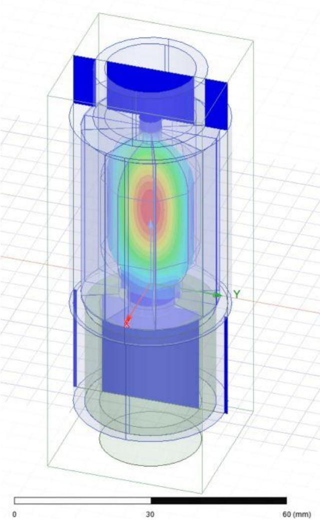
Parameter	Units	Baseline	High-Lumi
Energy CoM	GeV	250	250
Gradient	MeV/m	70	70
Beam Current	A	0.2	1.6
Beam Power	MW	2	16
Luminosity	$x10^{34}$	1.3	10.4
Beam Loading		45%	87%
RF Power	MW/m	30	125
Site Power	MW	~150	~180

Caution: **Requires serious investigation of beam dynamics - great topic for C^3 Demonstration R&D**

Energy

- Scalability studied to 3 TeV
- Requires rf pulse compression for reasonable site power
- Higher gradient option (155 MeV/m) in consideration

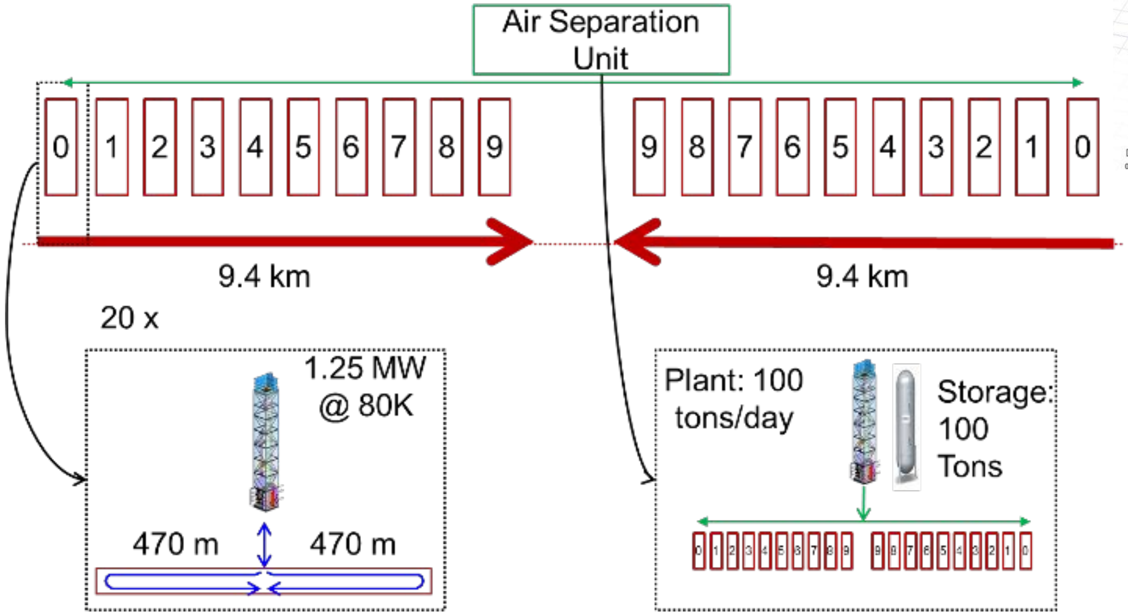
HTS Pulse Compressor
REBCO Coatings



Qo ~ 400k

Le Sage, CERN Collaborators

Cryogenics Scale to multi-TeV



arXiv:1807.10195 (2018)

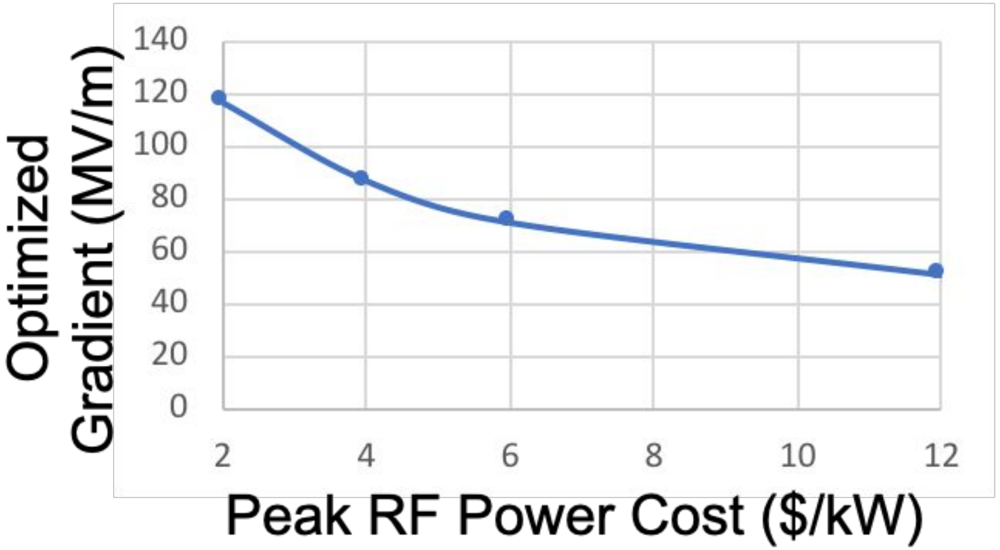
RF Source R&D Over the Timescale of the Next P5

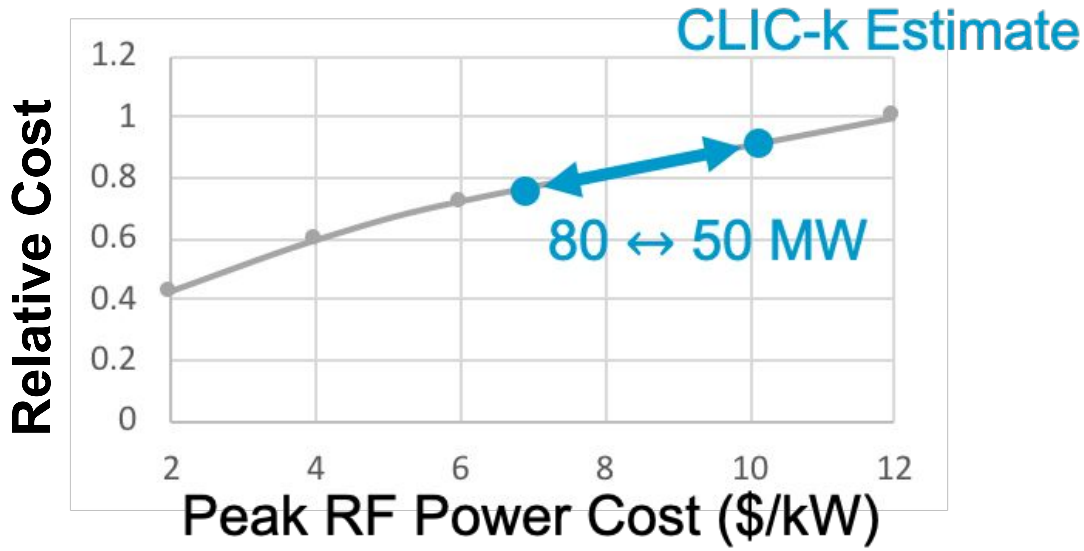
RF source cost is the key driver for gradient and cost

Significant savings when items procured at scale of LC

Need to focus R&D on reducing source cost to drive economic argument for high gradient

Gradient/Cost Scaling vs. RF Source Cost for Main Linac





Understand the Impact on Advanced Collider Concept Enabled by the Goals Defined in the DOE GARD RF Decadal Roadmap

https://science.energy.gov/~/media/hep/pdf/Reports/DOE_HEP_GARD_RF_Research_Roadmap_Report.pdf

RF Sources Available vs. Near Term Industrial Efforts

RF sources and modulators capable of powering CCC-250 commercially available

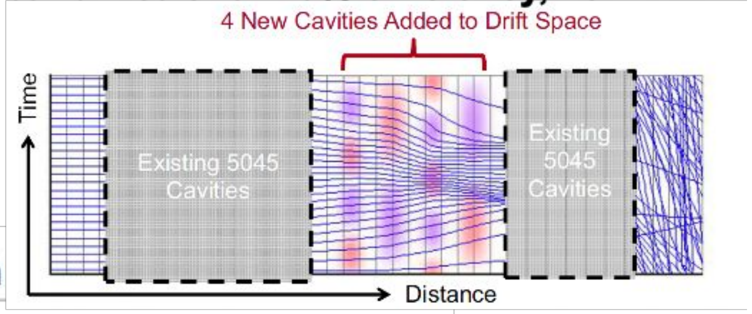
Plan to leverage significant developments in performance (HEIKA) of high power rf sources – requires industrialization

Los Alamos NATIONAL LABORATORY EST. 1943

New 50 MW peak power C-band klystron installed in September 2019

BVEI X-band 50 MW 57% COM Prototype

SLAC BAC Prototype
S-band Retrofit +10% efficiency, 73 MW

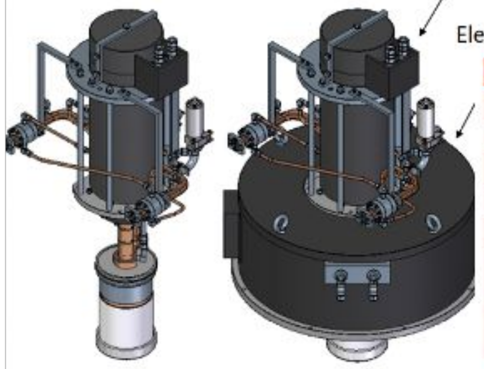


Near Term Industry

20-MW X-band Klystron

Klystron: E37116 Perveance : 1.25

Electromagnet: VT-68970



Parameter	Sim. Target	Design result
Beam voltage[kV]	265 (<290)	265
Beam current [A]	170.3 (<195)	170.3
Output power [MW]	>23	24.3
Efficiency [%]	>51	53.8
Drive power [W]	~120 (<400)	120
Max. electric field strength [kV/mm]	<64.5 (at 1.5 μs)	60.4
Stability	No reflected electrons	OK

* Actual efficiency is estimated to be 46 - 48%.

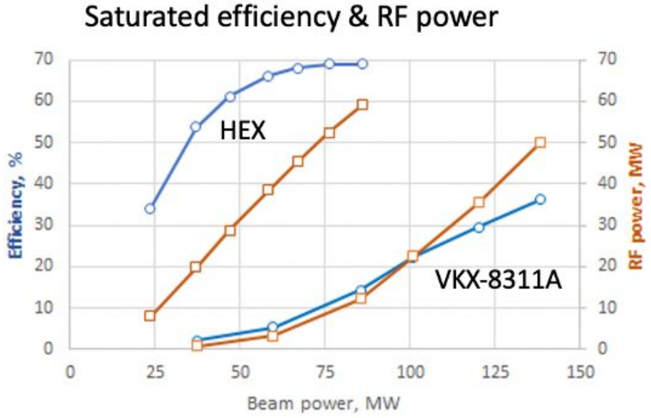
Canon
CANON ELECTRON TUBES & DEVICES CO., LTD.

Two tubes have been built and tested up to 20MW

High Efficiency Klystrons

Please See I. Syratchev's Talk for Many Great Examples from Designs to Prototypes

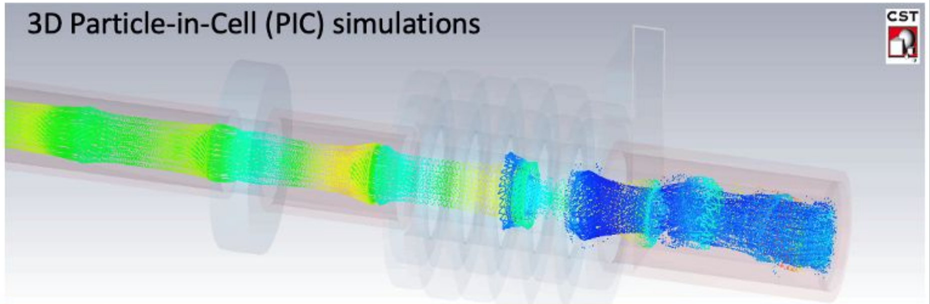
Retro-fit High Efficiency 50 MW, 12 GHz klystron (CERN/CPI).



- Re-used solenoid.
- Increased life time (> factor 2)
- Reduced modulator power (~ factor 2)
- Increased power gain (10 dB)
- Reduced solenoidal field

Prototype fabrication is under negotiation within CPI/INFN/CERN collaboration.

I. Syratchev, CLIC PM #41, 13.12.2021



	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316

https://indico.cern.ch/event/1101548/contributions/4635964/attachments/2363439/4034986/CLIC_PM_13_12_2021.pdf

Real Time Progress: CERN/Canon - Similar design with these simulation tool tested this week (Canon E37113) at 10 MW level and X-band

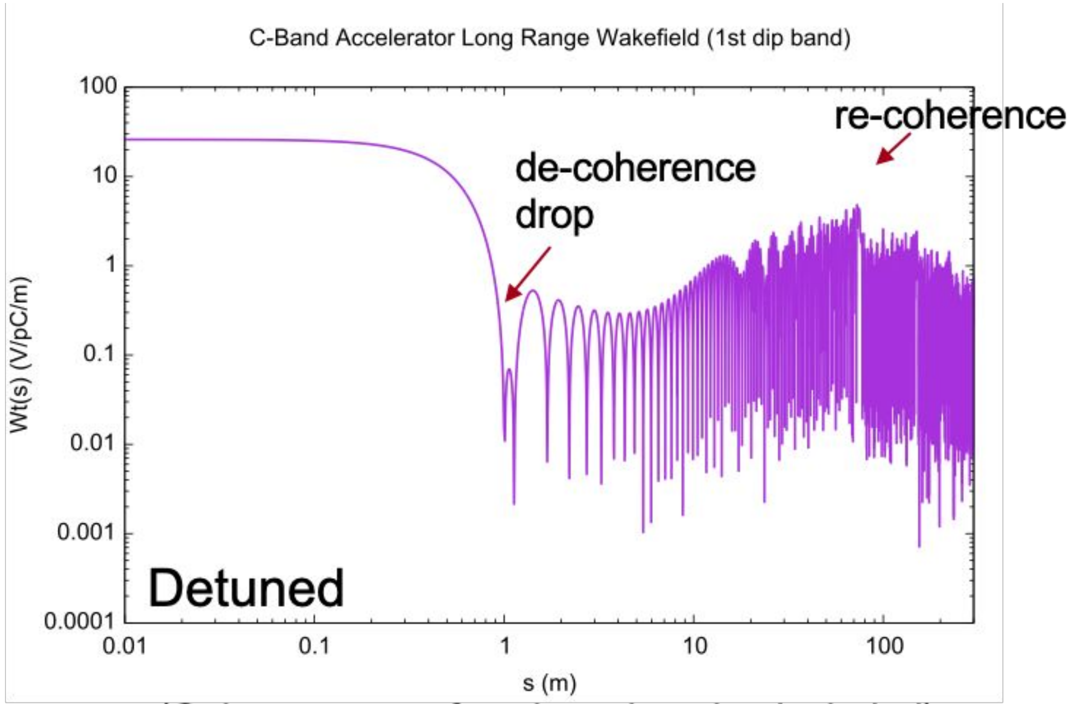
Gaussian Detuning Provides Required 1st Band Dipole Suppression for Subsequent Bunch, Damping Also Needed

Dipole mode wakefields immediate concern for bunch train

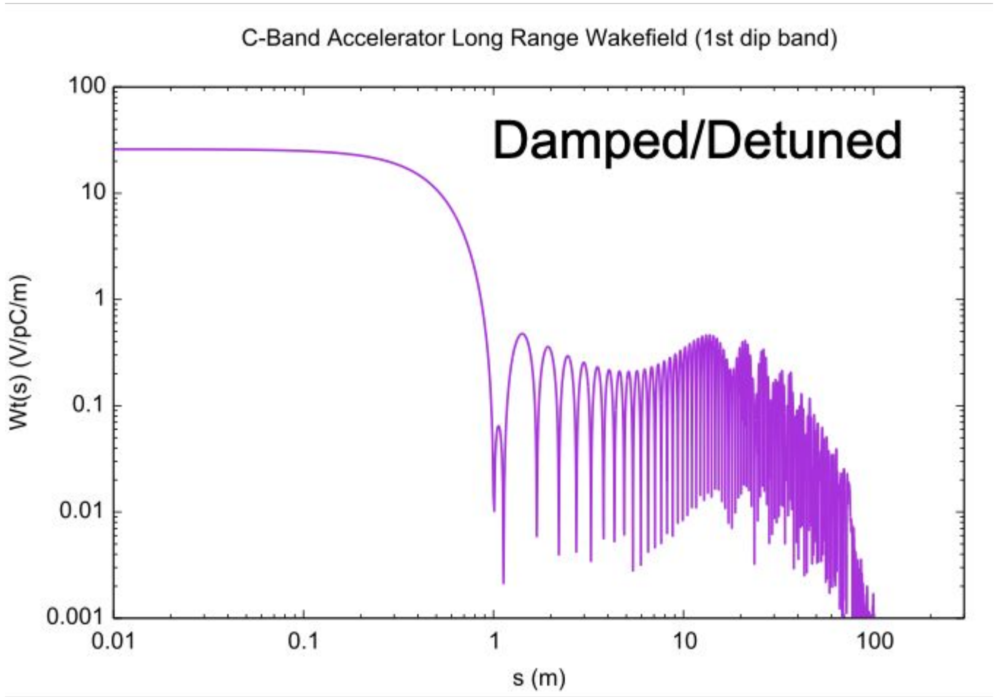
4σ Gaussian detuning of 80 cells for dipole mode (1st band) at f_c=9.5 GHz, w/ $\Delta f/f_c$=5.6%

First subsequent bunch s = 1m, full train ~75 m in length

- Damping needed to suppress re-coherence



(Only copper surface loss damping included)



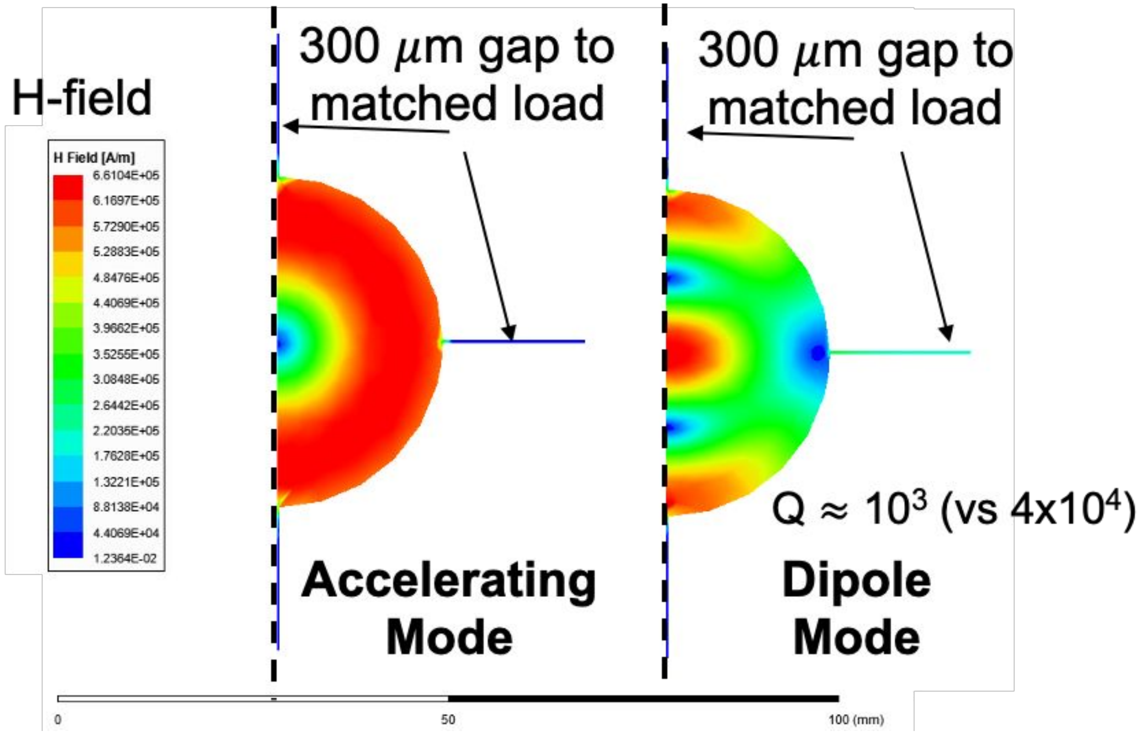
(1.0e3 Q total HOM damping included)

Distributed Coupling Structures Provide Natural Path to Implement Detuning and Damping of Higher Order Modes

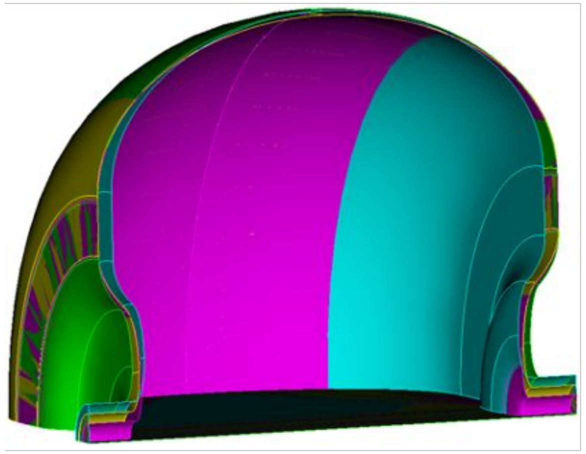
Individual cell feeds necessitate adoption of split-block assembly

Perturbation due to joint does not couple to accelerating mode

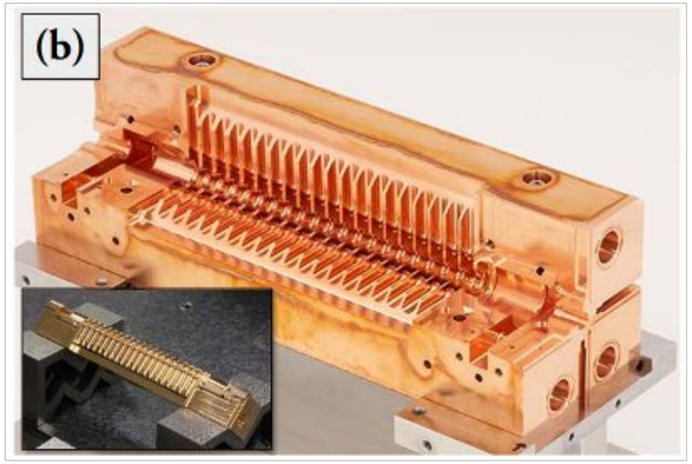
Exploring gaps in quadrature to damp higher order mode



Detuned Cavity Designs



Quadrant Structure



Abe et al., PASJ, 2017, WEP039

Outlook

C^3 Demonstration R&D Plan

C^3 demonstration R&D needed to advance technology beyond CDR level

Minimum requirement for Demonstration R&D Plan:

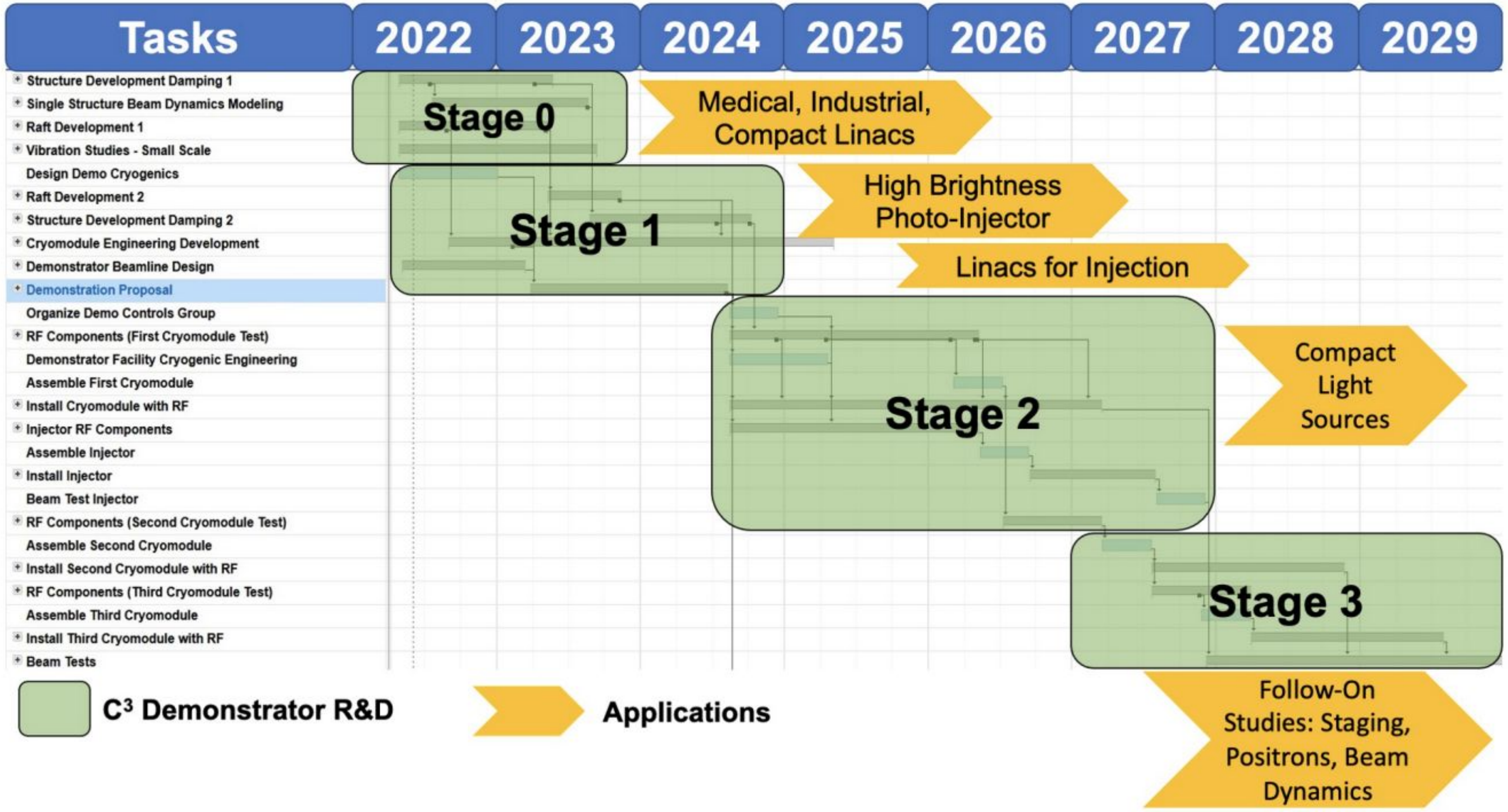
- **Demonstrate operation of fully engineered and operational cryomodule**
  - Simultaneous operations of min. 3 cryomodules
- Demonstrate operation during cryogenic flow equivalent to main linac at full liquid/gas flow rate
- Operation with a multi-bunch photo injector - high charges bunches to induce wakes, tunable delay witness bunch to measure wakes
- Demonstrate full operational gradient 120 MeV/m (and higher > 155 MeV/m) w/ single bunch
  - Must understand margins for 120 - targeting power for (155 + margin) 170 MeV/m
  - 18X 50 MW C-band sources - off the shelf units
- **Fully damped-detuned accelerating structure**
- Work with industry to develop C-band source unit optimized for installation with main linac

This demonstration directly benefits development of compact FELs, beam dynamics, high brightness guns, *etc.*

The other elements needed for a linear collider - the sources, damping rings, and beam delivery system – more advanced from the ILC and CLIC – need C^3 specific design

- Our current baseline uses these directly; will look for further cost-optimizations for of C^3

C^3 Demonstration R&D Plan timeline

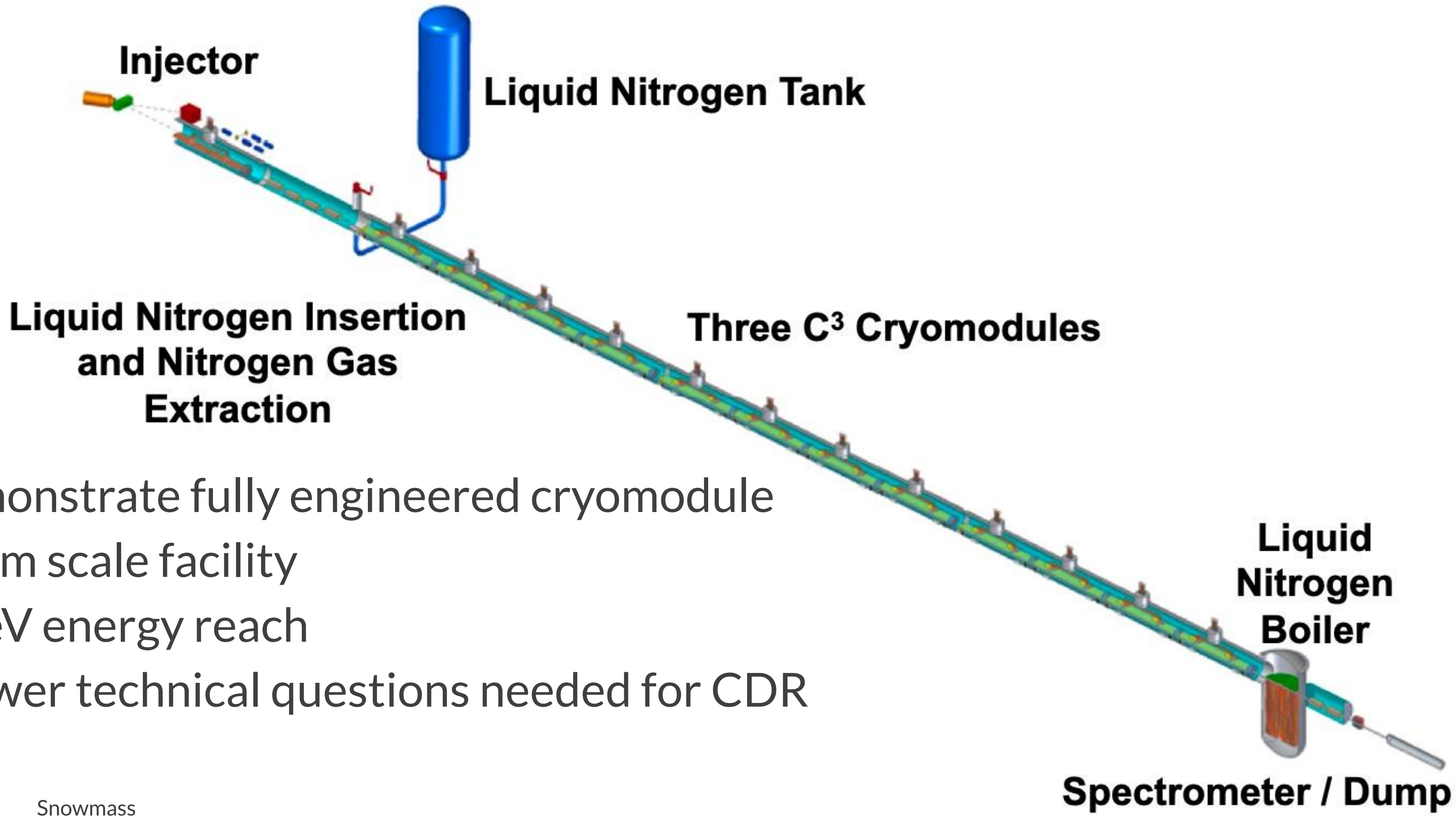


C^3 R&D, System Design and Project Planning are ongoing

- Early career scientists should help drive the agenda for an experiment they will build/use
- Many opportunities for other institutes to collaborate on:
  - beam dynamics, vibrations and alignment, cryogenics, rf engineering, controls, detector optimization, background studies, etc.

High Energy Physics: Caterina Vernieri caterina@slac.stanford.edu
Accelerator Science & Engineering: Emilio Nanni nanni@slac.stanford.edu

The Complete C^3 Demonstrator



Demonstrate fully engineered cryomodule

~50 m scale facility

3 GeV energy reach

Answer technical questions needed for CDR

Conclusion

1st C^3 Workshop
https://indico.slac.stanford.edu/event/7016/

2nd C^3 Workshop
https://indico.fnal.gov/event/54189/

C^3 can provide a rapid route to precision Higgs physics with a compact 8 km footprint

- Higgs physics run by 2040
- Possibly, a US-hosted facility

C^3 time structure is compatible with SiD-like detector overall design and ongoing optimizations.

C^3 can be quickly be upgraded to 550 GeV

C^3 can be extended to a 3 TeV e+e- collider with capabilities similar to CLIC

Possible to do physics at an intermediate stage in the construction at 91 GeV

- We do not consider this a part of our baseline, but we mention the possibility in case there is community interest for a Giga-Z (2 yrs) program

Next workshop proposed dates Oct. 13-14th 2022

More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

Questions?